

J/Ψ production relative to the reaction plane in Pb-Pb collisions at the CERN SPS

Francesco Prino

INFN - Sezione di Torino

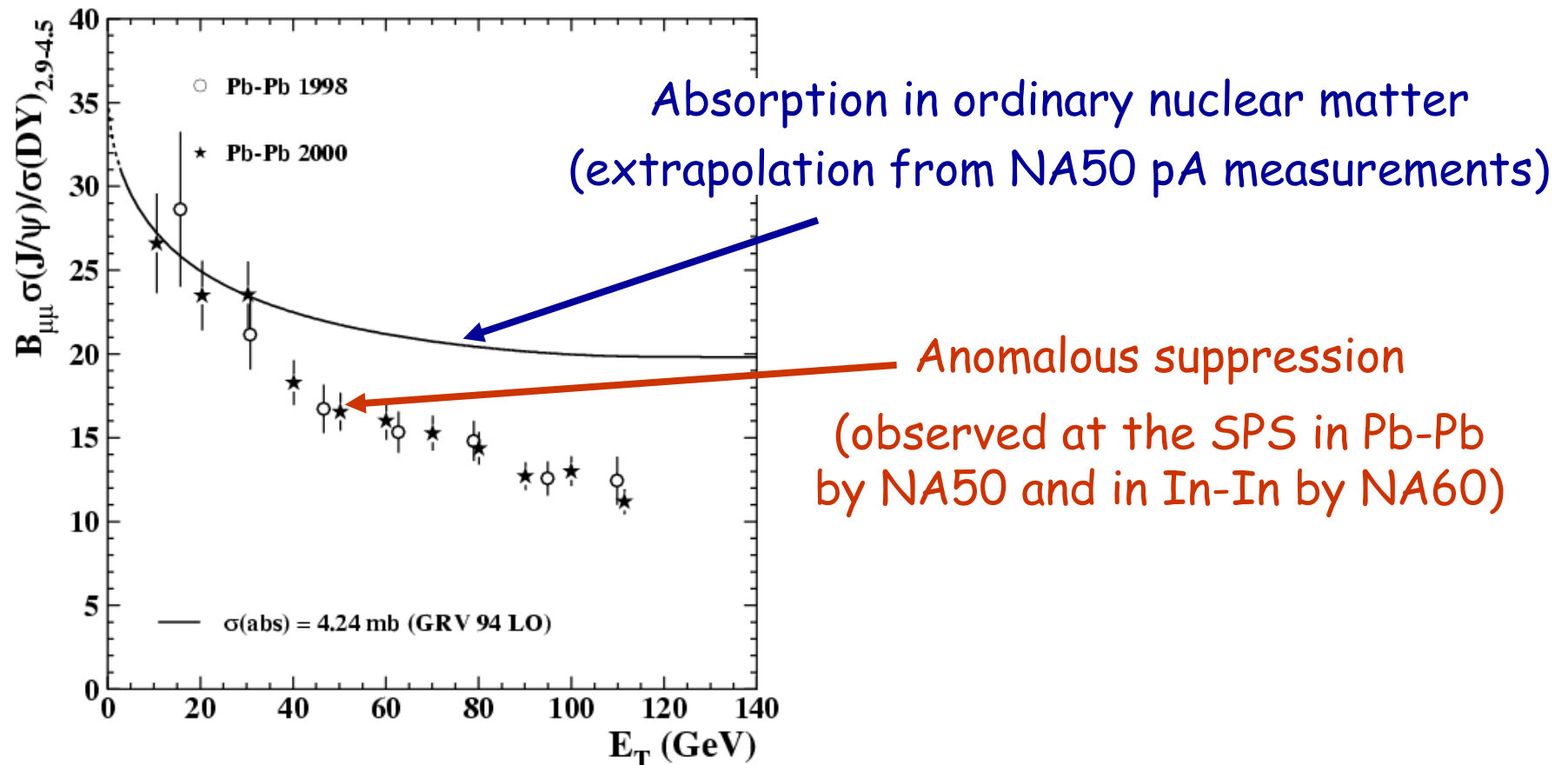
for the NA50 collaboration



Hard Probes 2006, Asilomar, June 14th 2006

Physics motivation

J/ψ anomalous suppression



- Proposed mechanisms for anomalous suppression:
 - ⇒ Charmonium dissociation in the QGP (Matsui, Satz, PLB178 (1986) 416)
 - ⇒ Break-up by co-moving hadrons (Armesto, Capella, PLB430 (1998) 23)
- J/ψ azimuthal anisotropy relative to the reaction plane
 - could help to distinguish between these 2 mechanisms

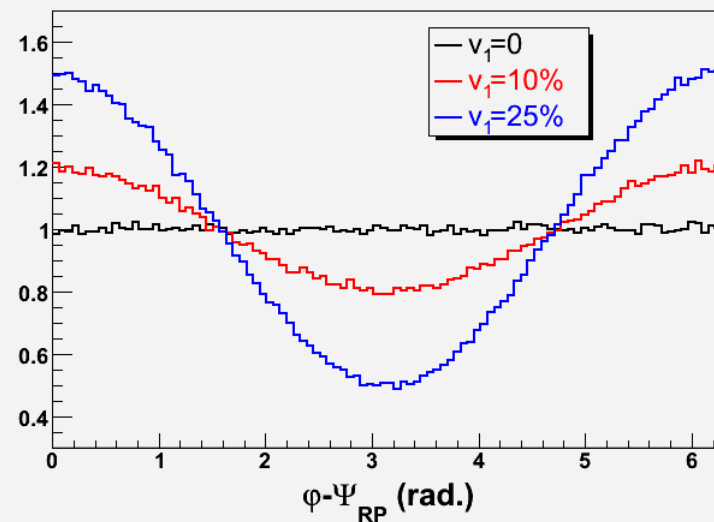
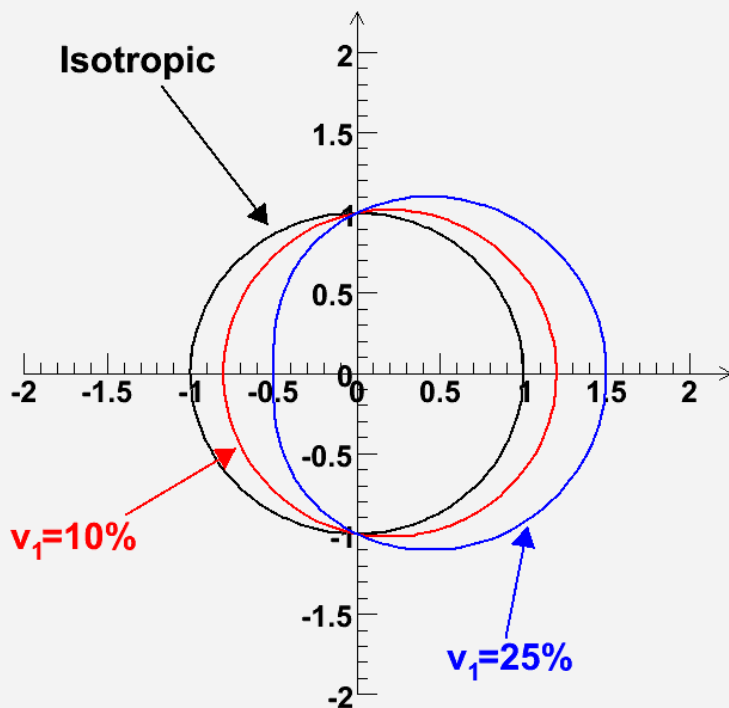
Observables: v_1

- Anisotropy in the observed particle azimuthal distribution due to correlations between the azimuthal angle of the outgoing particles and the direction of the impact parameter

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi} (1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos(2(\varphi - \Psi_{RP})) + \dots)$$

Directed flow coefficient

$$v_1 = \langle \cos(\varphi - \Psi_{RP}) \rangle$$



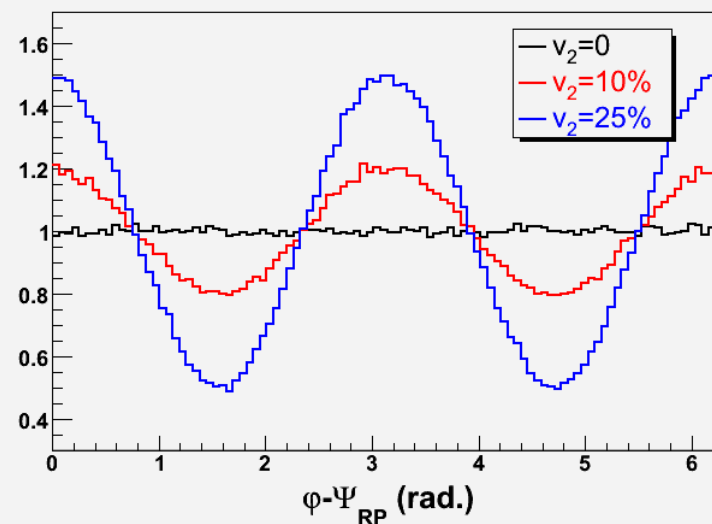
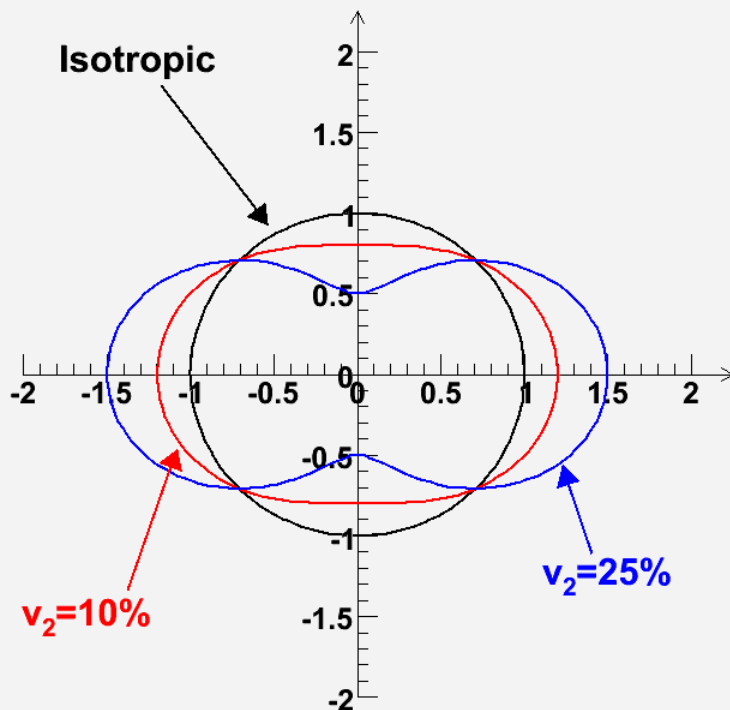
Observables: v_2

- Anisotropy in the observed particle azimuthal distribution due to correlations between the azimuthal angle of the outgoing particles and the direction of the impact parameter

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi} (1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos(2(\varphi - \Psi_{RP})) + \dots)$$

Elliptic flow coefficient

$$v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle$$



Possible sources of J/Ψ v_2

1) Charm *elliptic flow*

- ⇒ Flow = collective motion superimposed to thermal motion
- ⇒ for J/Ψ formed by $c\bar{c}$ recombination
- ⇒ if c quarks are early-thermalized



Not likely to occur at SPS energies

📖 Greco, Ko, Rapp, PLB595 (2004) 202

2) $c\bar{c}$ break-up on *co-moving hadrons*

- ⇒ More pions in-plane than out-of-plane
 - ✓ *due to pion elliptic flow*
- ⇒ J/Ψ exiting in-plane more absorbed



Give rise to **negative** values of v_2 with smooth centrality dependence

📖 Heiselberg, Mattiello, PRC60 (1999) 44902

3) $c\bar{c}$ break-up by *QGP hard gluons*

- ⇒ parton density azimuthally anisotropic
- ⇒ J/Ψ exiting out-of-plane more absorbed



Give rise to **positive** values of v_2 with sudden onset at the centrality for which the critical conditions for QGP are attained

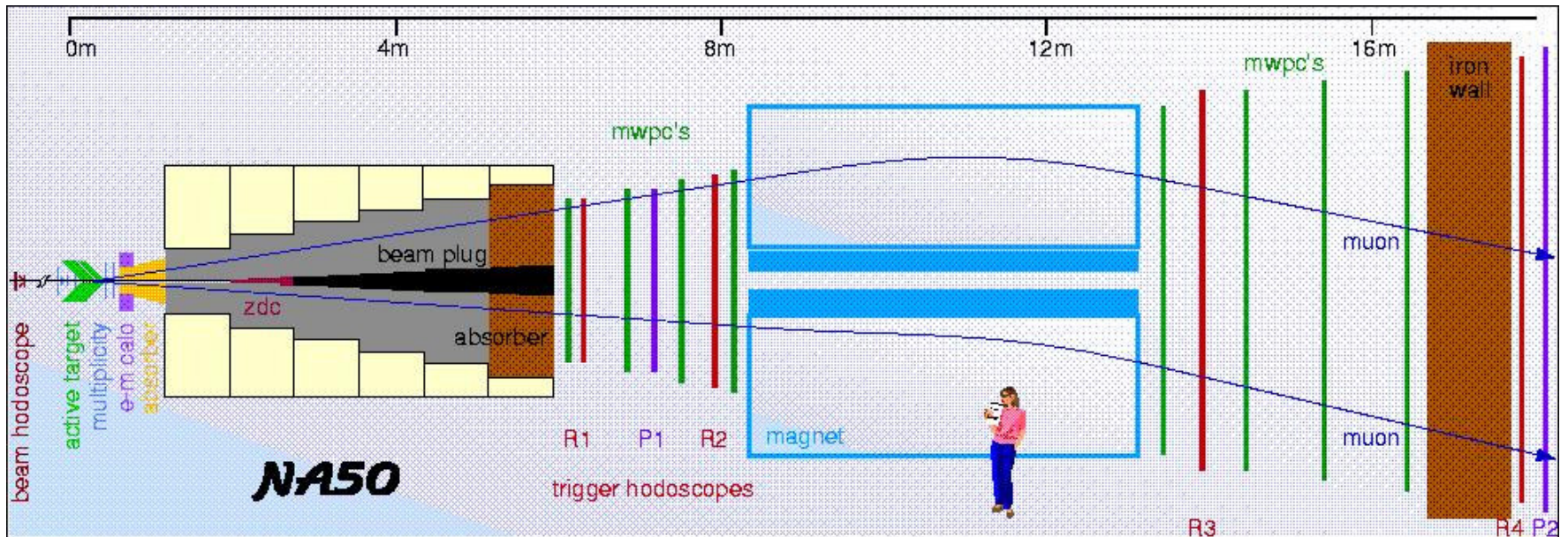
📖 Wang, Yuan, PLB540 (2002) 62

📖 Zhu, Zhuang, Xu, PLB607 (2005) 207

Experimental setup

NA50 setup – year 2000

Study of muon pair production in Pb-Pb collisions

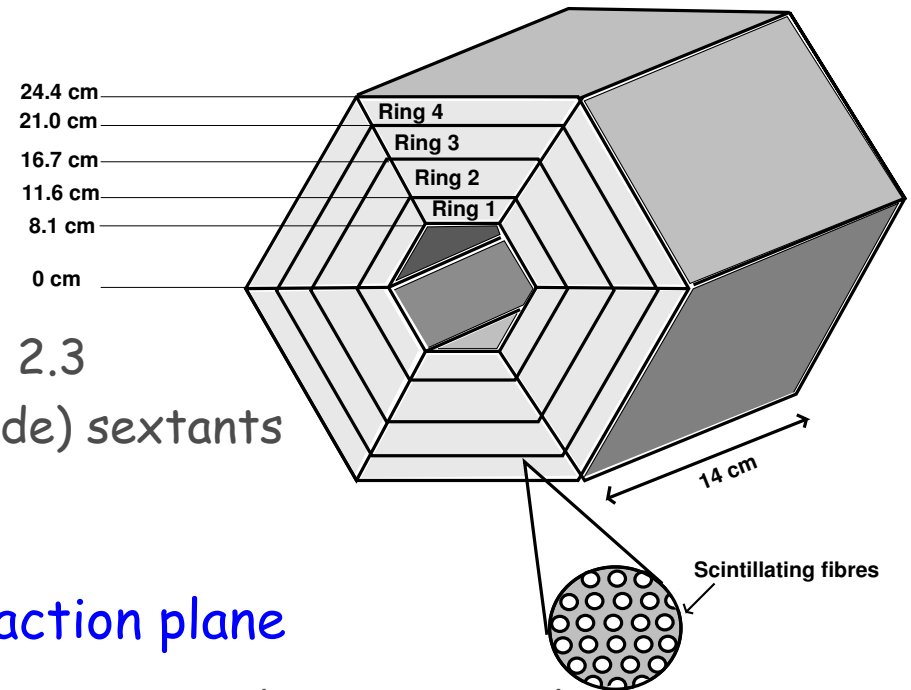


- Pb beam
 - ⇒ $E_{\text{beam}} = 158 \text{ GeV/nucleon}$
- Beam detectors
- Pb target in vacuum
 - ⇒ thickness = 4 mm
- Centrality detectors
 - ⇒ EM calorimeter ($1.1 < \eta_{\text{lab}} < 2.3$)
 - ⇒ Multiplicity Detector ($1.1 < \eta_{\text{lab}} < 4.2$)
 - ⇒ Zero Degree Calorimeter ($\eta_{\text{lab}} > 6.3$)
- Muon spectrometer ($2.7 < \eta_{\text{lab}} < 3.9$)
 - ⇒ toroidal magnet+MWPC+hodoscopes

Reaction plane estimation

- Electromagnetic calorimeter

- ⇒ Measures neutral (γ and π^0) E_T
- ⇒ Made of Pb and scintillating fibers
- ⇒ Distance from target: 20 cm
- ⇒ Pseudorapidity coverage: $1.1 < \eta_{\text{lab}} < 2.3$
- ⇒ Azimuthal segmentation: 6 (60° wide) sextants
- ⇒ Radial segmentation: 4 rings



- Event plane Ψ_n = estimator of the reaction plane

- ⇒ Exploit anisotropy of produced E_T to estimate the reaction plane

$$\Psi_n = \frac{1}{n} \tan^{-1} \left(\frac{\sum_{i=1}^6 E_T^i \sin(n\varphi_i)}{\sum_{i=1}^6 E_T^i \cos(n\varphi_i)} \right)$$

- ⇒ n = Fourier harmonic, φ_i = central azimuth of sextant i , $E_T^i = E_T$ in sextant i
- ⇒ several methods to estimate event-plane resolution under study

Event plane direction

- Electromagnetic calorimeter in the backward rapidity region

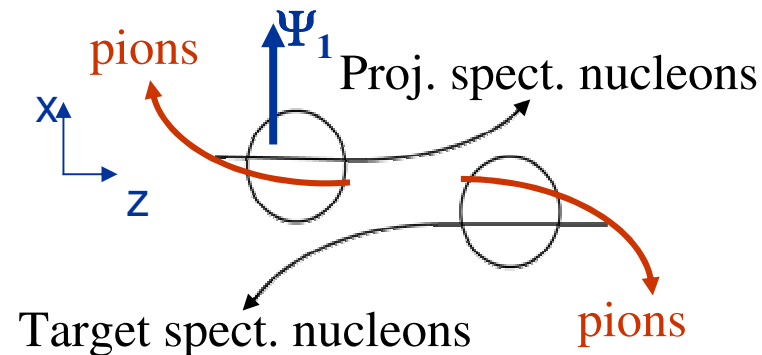
⇒ v_1 of pions in the backward region is positive (NA49, WA98)

✓ *pions flow in the opposite direction with respect to spectator nucleons*

⇒ Event plane Ψ_1 directed:

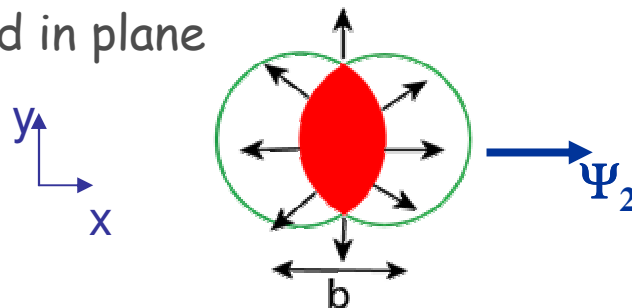
✓ *opposite to the direction of spectator nucleons in the backward hemisphere*

✓ *along the direction of spectator nucleons in the forward hemisphere*



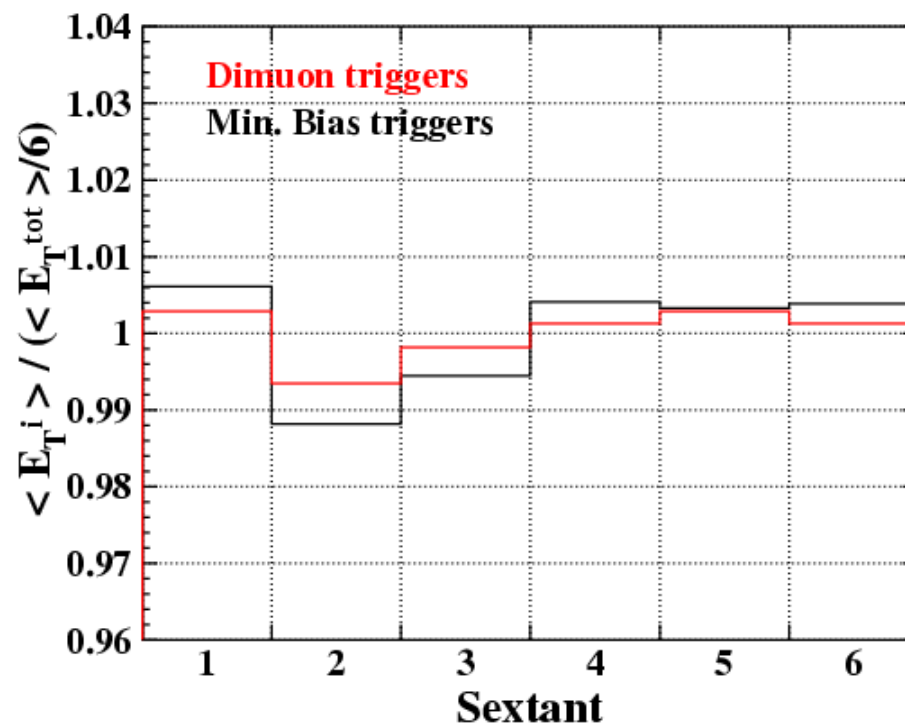
⇒ v_2 of pions in the backward region is positive (NA49, CERES)

⇒ event plane Ψ_2 directed in plane



Event plane flattening

- Event plane azimuthal distribution should be flat (isotropic)
 - ⇒ no preferential direction for the impact parameter
- Acceptance correction
 - ⇒ Flattening by weighting each sextant with the inverse of $\langle E_T \rangle$ measured by that sextant (📖 Poskanzer, Voloshin, PRC58 (1998) 62)
 - ⇒ very small correction (practically uniform calorimeter azimuthal acceptance)



Analysis techniques

Analysis strategy

- Need to separate J/Ψ from background dimuons
 - ⇒ Background dimuons in J/Ψ mass range $\approx 5\text{-}15\%$ (depending on centrality)
- Two kinds of analysis
 - ⇒ Extract number of J/Ψ in bins of azimuthal angle
 - ✓ *2 different methods for background subtraction*
 - ⇒ Estimate J/Ψ Fourier coefficients v_1 and v_2
 - ✓ *2 different methods to calculate v_1 and v_2*

	$10 < E_T < 30$		$50 < E_T < 70$		$90 < E_T < 120$	
J/ψ	15556	(95.8%)	18656	(90.9%)	18717	(86.0%)
ψ'	6	(0.0%)	6	(0.0%)	2	(0.0%)
DY	392	(2.4%)	673	(3.3%)	855	(4.0%)
$D\bar{D}$	108	(0.7%)	203	(1.0%)	178	(0.8%)
COMBIN.	171	(1.1%)	979	(4.8%)	2004	(9.2%)
Background	677	(4.2%)	1861	(9.1%)	3039	(14.0%)
S/B	23.0		10.0		6.2	
$S/\sqrt{S+B}$	122		130		127	

Number of J/Ψ in azimuthal bins

Method 1 = “Fitting”

- Build mass spectra of dimuons in bins of:

- ⇒ centrality (E_T)
- ⇒ azimuthal angle relative to the event plane ($\Delta\Phi_n = \Phi_{\text{dimu}} - \Psi_n$)

- Fit to dimuon mass spectra

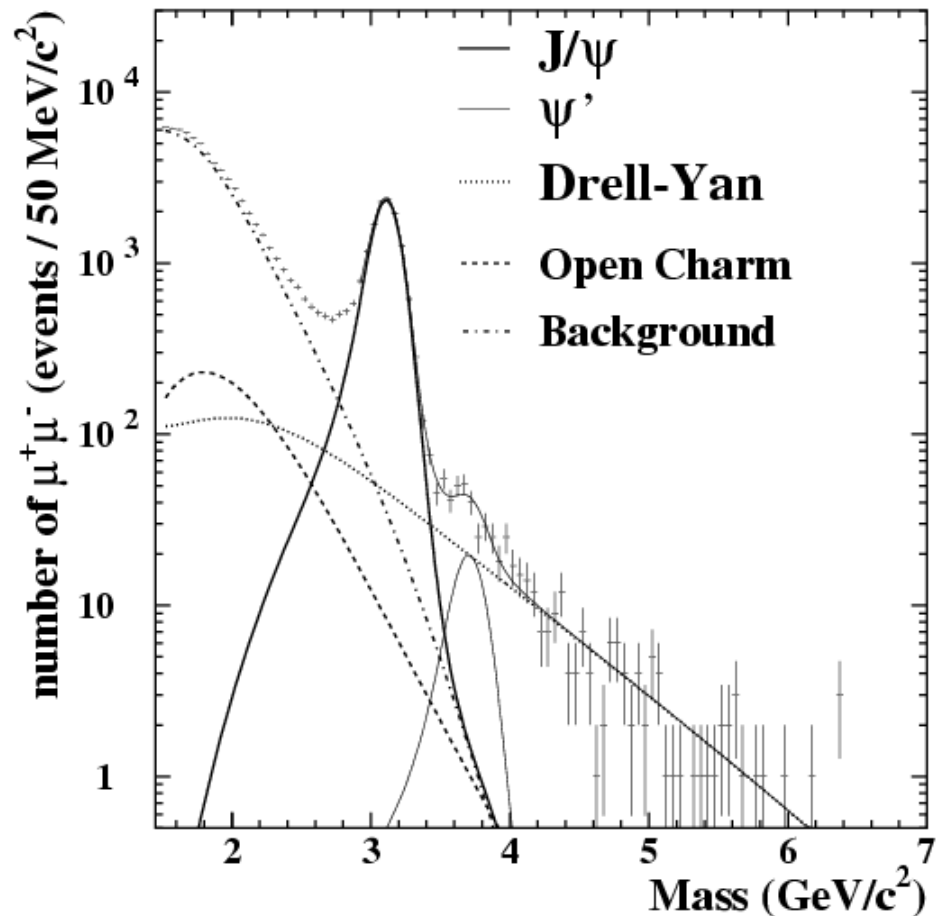
- ⇒ 5 components

- ✓ J/Ψ , Ψ' , DY, open charm, combinatorial background
- ✓ functional forms from Monte Carlo simulations with detailed description of the NA50 setup

- ⇒ 6 free parameters

- ✓ 4 normalizations + J/Ψ mass and width

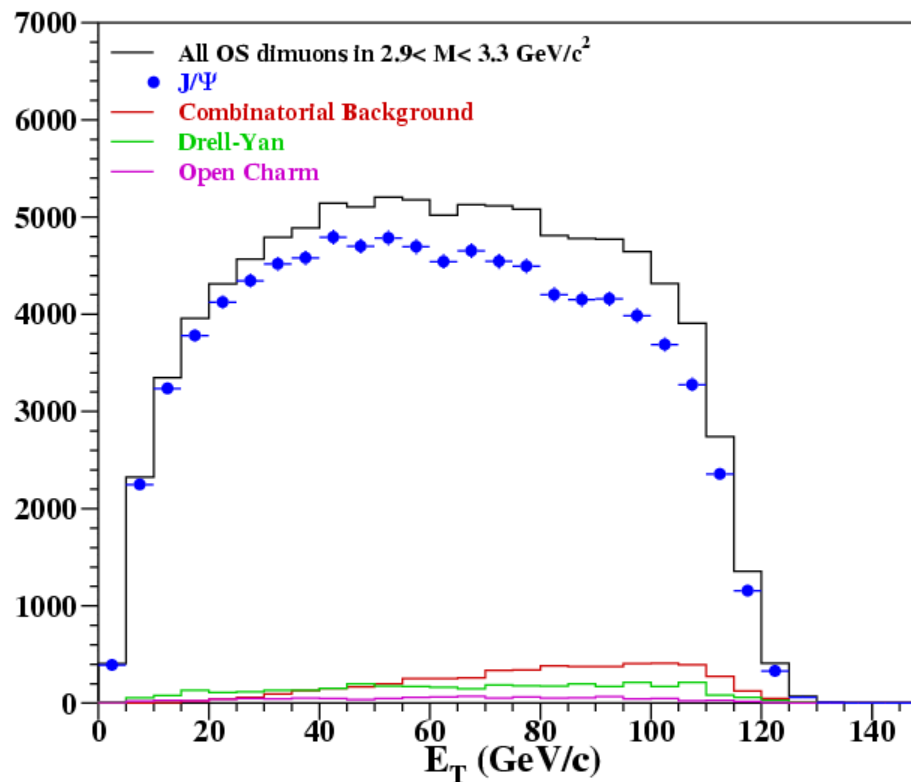
- ⇒ Limited by DY statistics.



Number of J/Ψ in azimuthal bins

Method 2 = “Counting”

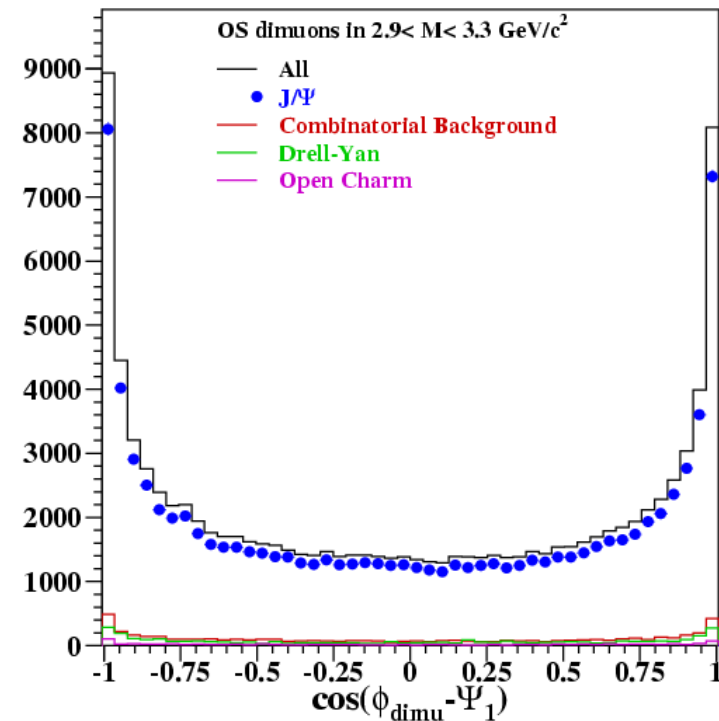
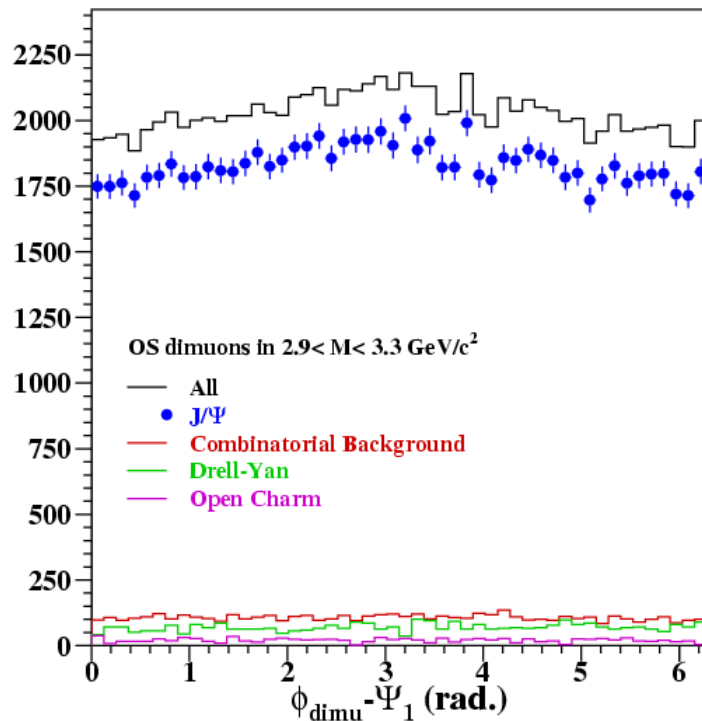
- Build E_T spectra of Opposite Sign dimuons with $2.9 < M < 3.3 \text{ GeV}/c^2$ in bins of azimuthal angle relative to the event plane and subtract:
 - \Rightarrow *Combinatorial bck* \rightarrow from Like Sign dimuons in $2.9 < M < 3.3 \text{ GeV}/c^2$
 - \Rightarrow *DY* \rightarrow from Opposite Sign dimuons in $M > 4.2 \text{ GeV}/c^2$
 - \Rightarrow *Open Charm* \rightarrow from Opposite Sign dimuons in $2.2 < M < 2.6 \text{ GeV}/c^2$



Estimate J/Ψ v_n

Method 1 = “Cosine spectra”

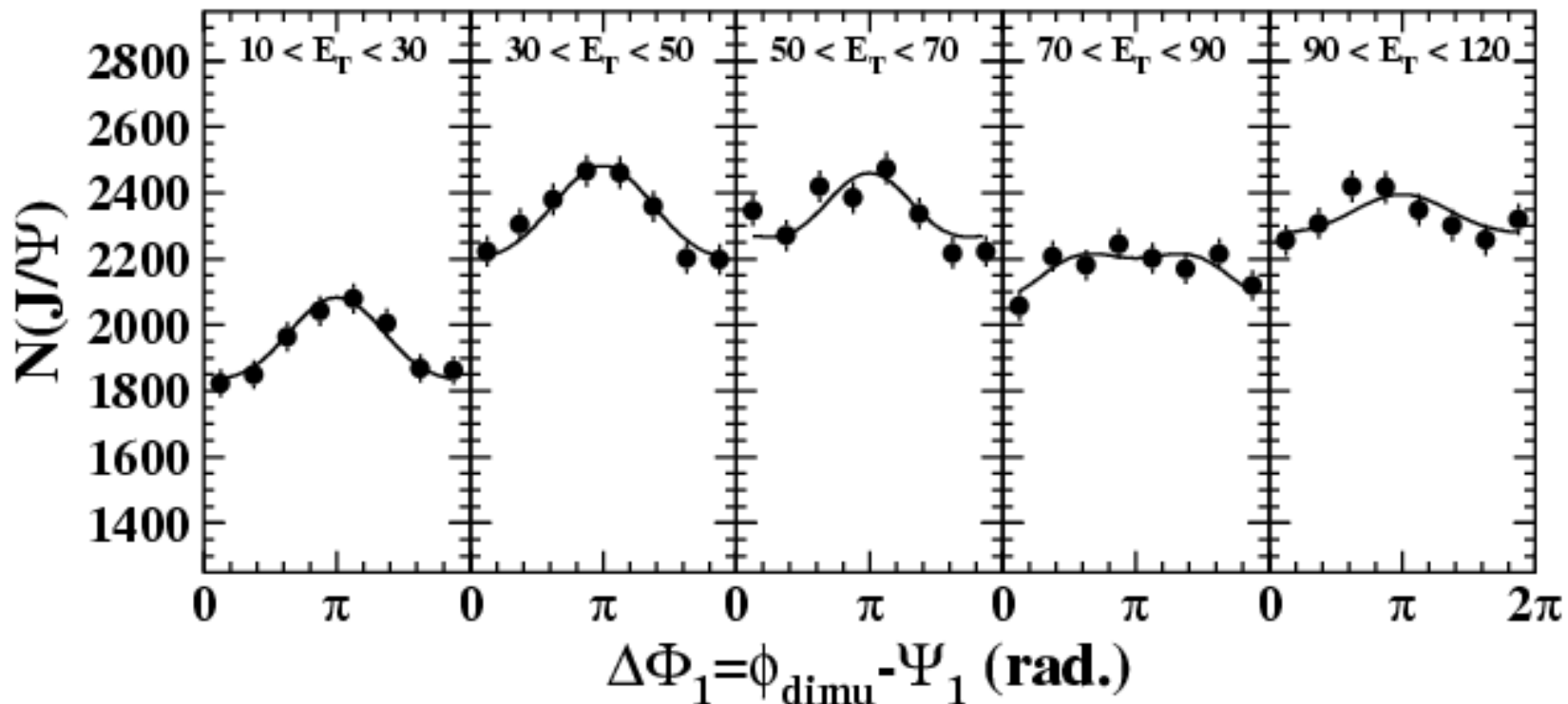
- Build $\cos[n(\Phi_{\text{dimu}} - \Psi_n)]$ spectra of dimuons with $2.9 < M < 3.3 \text{ GeV}/c^2$ in E_T (p_T) bins
 - ⇒ Subtract combinatorial bck, DY and open charm $\cos[n(\Phi_{\text{dimu}} - \Psi_n)]$ spectra
- Calculate $v'_n = \langle \cos[n(\Phi_{\text{dimu}} - \Psi_n)] \rangle$
 - ⇒ need to correct for event plane resolution to obtain v_n (*under investigation*)
 - ⇒ v'_n always smaller than v_n



Estimate J/Ψ v_n

Method 2 = “Fit to $N^{J/\Psi}$ in azimuthal bins”

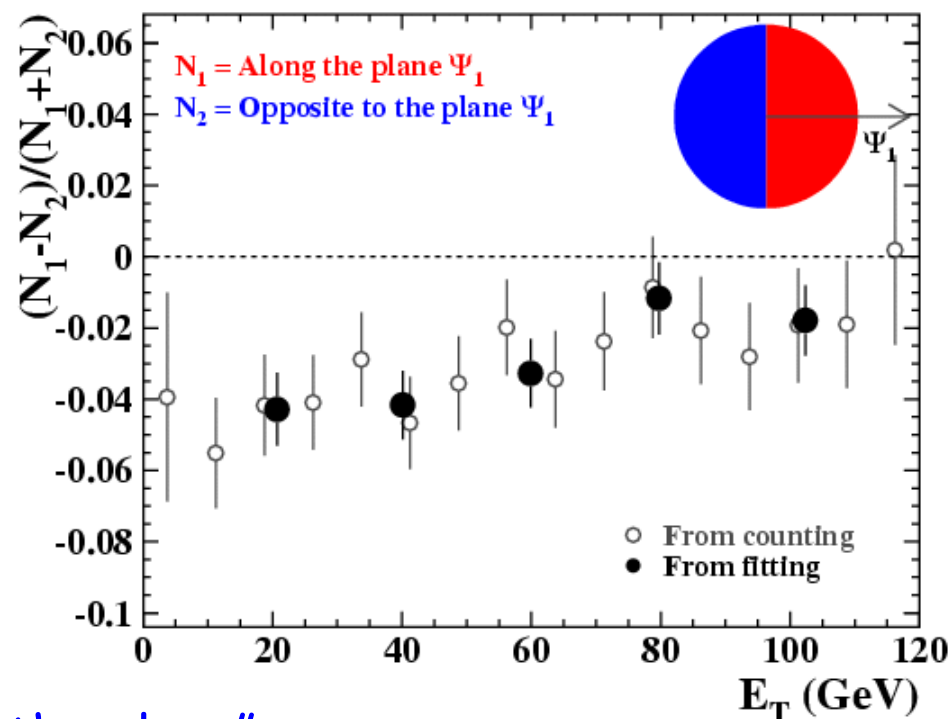
- Count dimuons in $2.9 < M < 3.3 \text{ GeV}/c^2$ in bins of E_T and $\Delta\Phi_n = \Phi_{\text{dimu}} - \Psi_n$
 - ⇒ Subtract combinatorial bck, DY and open charm
- Fit with:
 - ⇒ $dN/d\Delta\Phi_1 = A[1 + 2 v_1 \cos(\Delta\Phi_1) + 2 v_2 \cos(2 \cdot \Delta\Phi_1)]$
 - ⇒ $dN/d\Delta\Phi_2 = A[1 + 2 v_2 \cos(2 \cdot \Delta\Phi_2)]$



Preliminary results

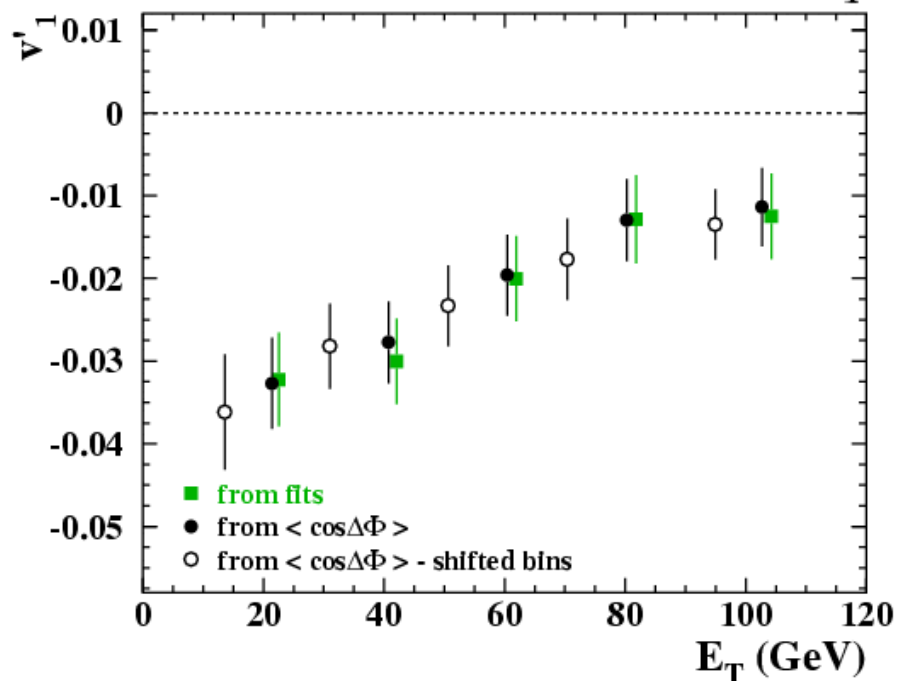
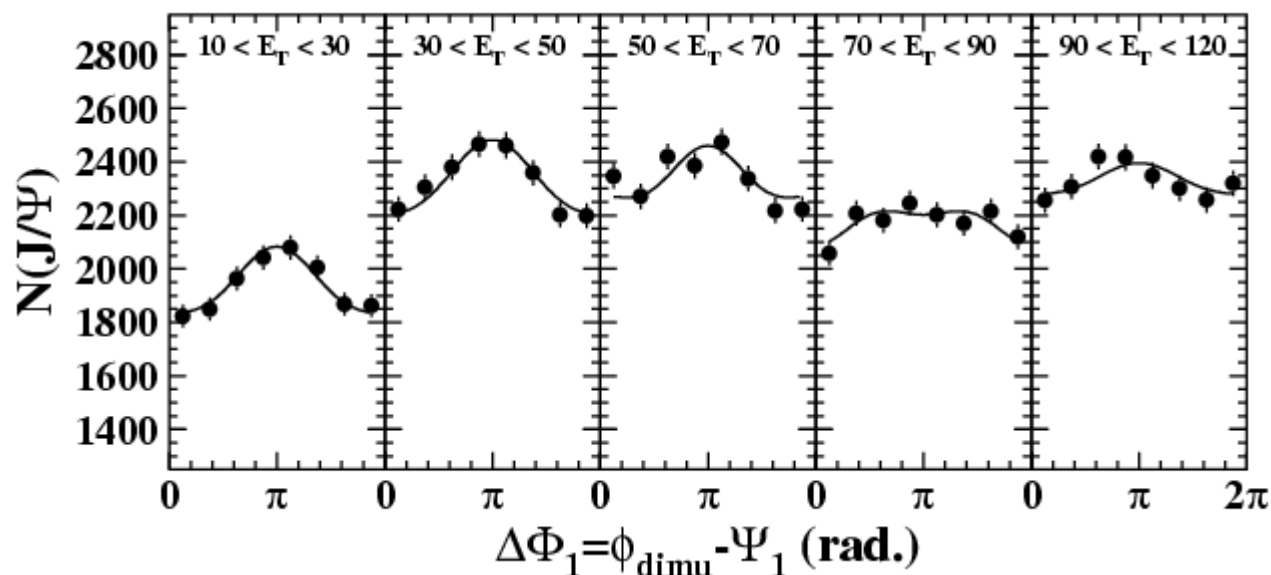
Directed anisotropy (I)

E_T range (GeV)	$N^{\text{reco}}(\text{J}/\Psi)$ along Ψ_1	$N^{\text{reco}}(\text{J}/\Psi)$ opposite Ψ_1
10-30	8600	9300
30-50	10200	11100
50-70	10400	11100
70-90	9900	10100
90-120	10600	11000



- More J/Ψ 's emitted "opposite to the plane"
 - ⇒ negative J/Ψ v_1
 - ⇒ more J/Ψ 's in the azimuthal region where there are more pions
 - ⇒ Anisotropy decreases with increasing centrality
- Unexpectedly large anisotropy **BUT** momentum conservation effects not taken into account
- Good agreement between the 2 analysis methods

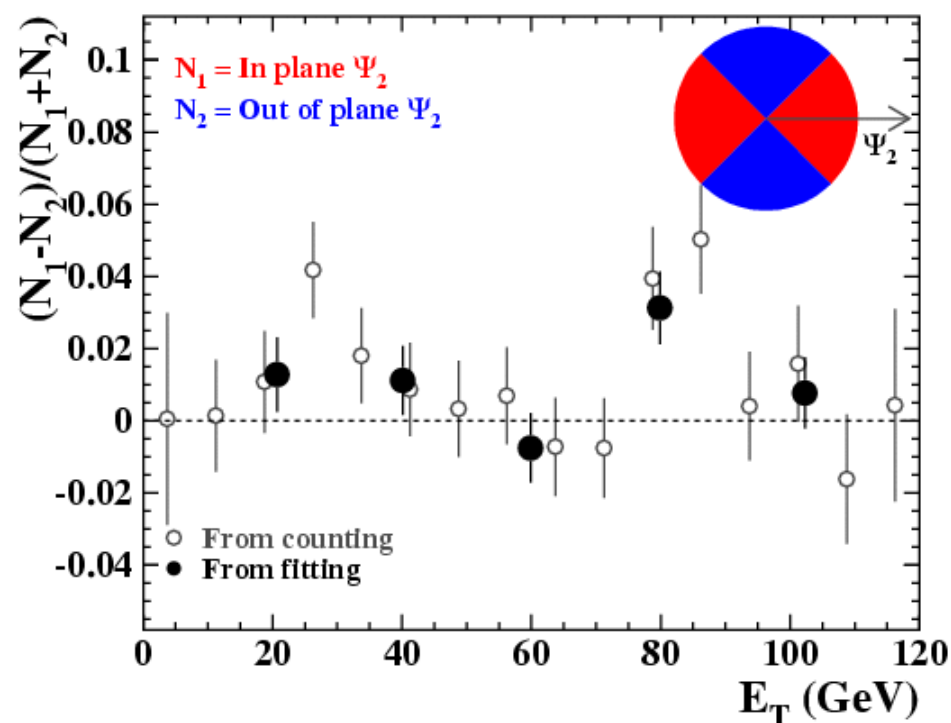
Directed anisotropy (II)



- Systematic effects being evaluated
 - ⇒ No event-plane resolution correction
 - ⇒ No momentum conservation correction
- Negative J/Ψ v_1
 - ⇒ same v_1 sign as for pions
 - ⇒ more J/Ψ in the azimuthal region opposite to projectile spectator bounce-off direction
- Good agreement between the 2 analysis methods

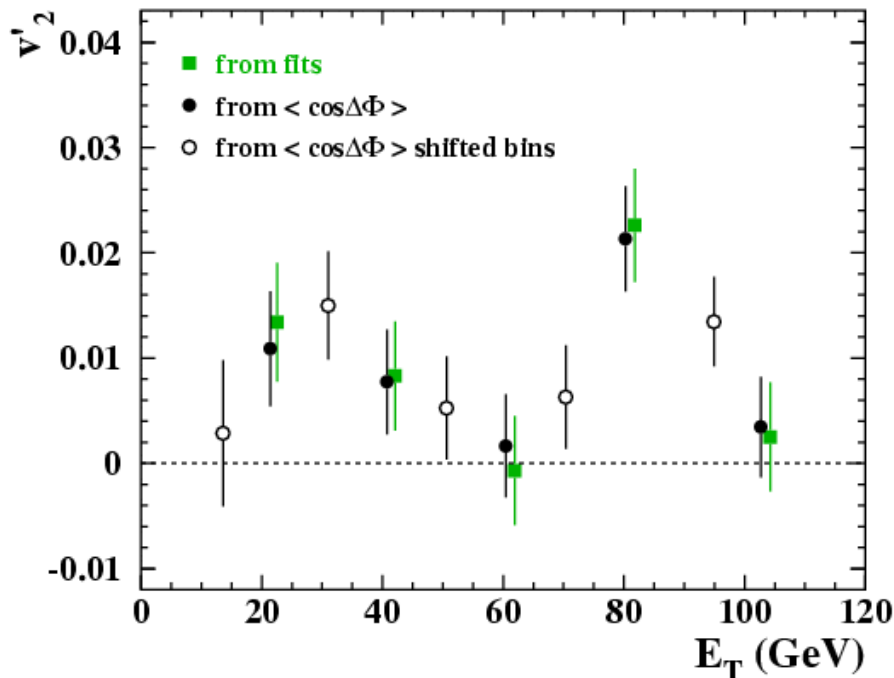
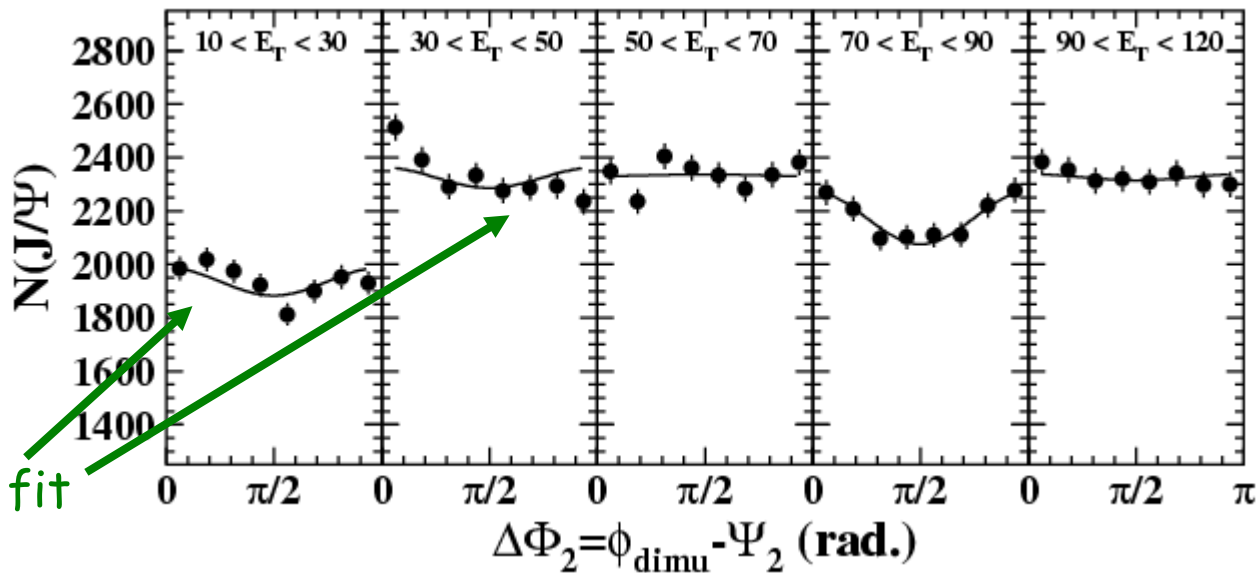
Elliptic anisotropy (I)

E_T range (GeV)	$N^{\text{reco}}(\text{J}/\Psi)$ in plane	$N^{\text{reco}}(\text{J}/\Psi)$ out of plane
10-30	9100	8900
30-50	10700	10500
50-70	10700	10800
70-90	10300	9700
90-120	10900	10700



- Slightly more J/ Ψ 's emitted "in plane"
 \Rightarrow negative v_2 (i.e. more J/ Ψ observed out-of-plane) seems excluded
- Good agreement between the 2 analysis methods

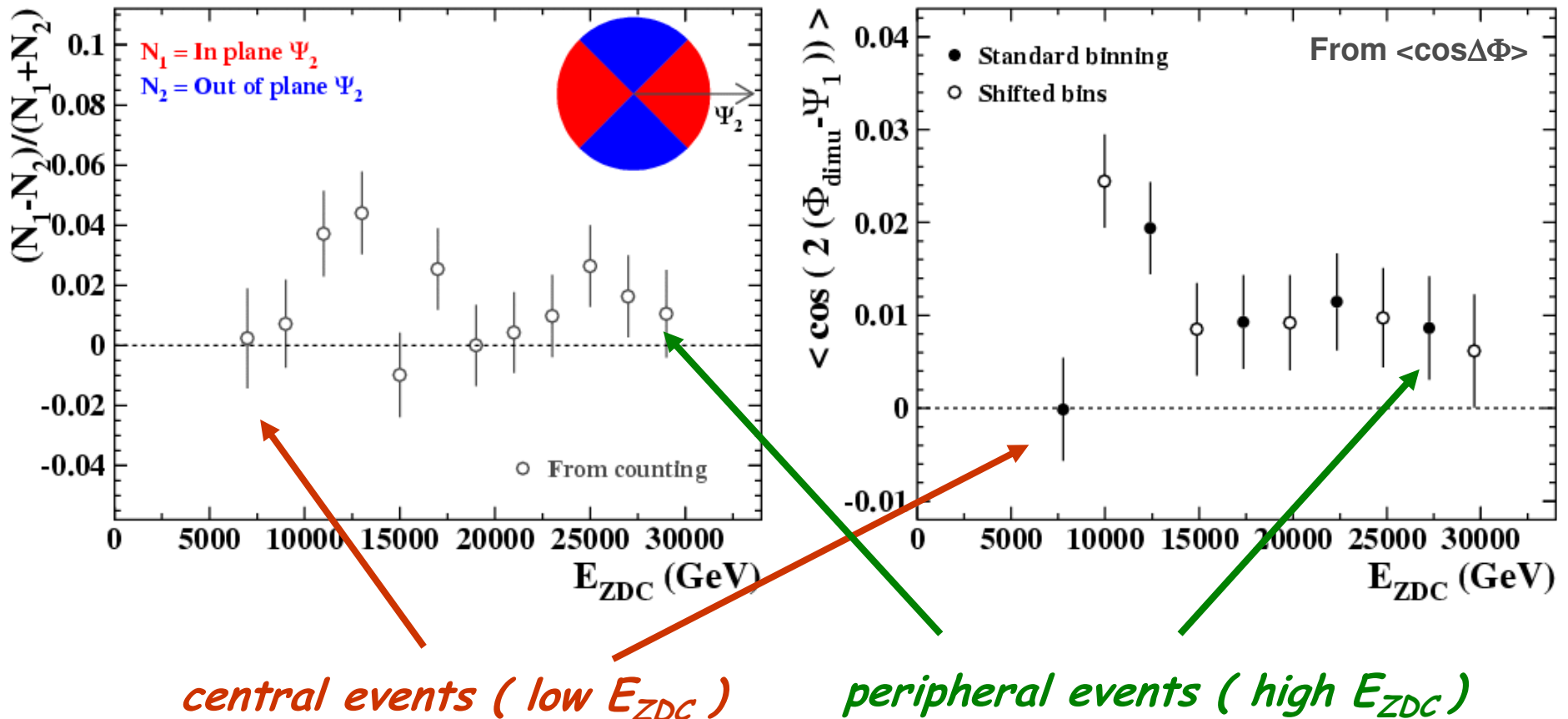
Elliptic anisotropy (II)



- Small positive J/Ψ v_2 on average
 \Rightarrow more J/Ψ 's exiting in plane
- Negative J/Ψ v_2 excluded
 \Rightarrow exclude a major role for breakup by co-movers
- Systematic effects being evaluated
 \Rightarrow No event-plane resolution correction
- Good agreement between the 2 analysis methods

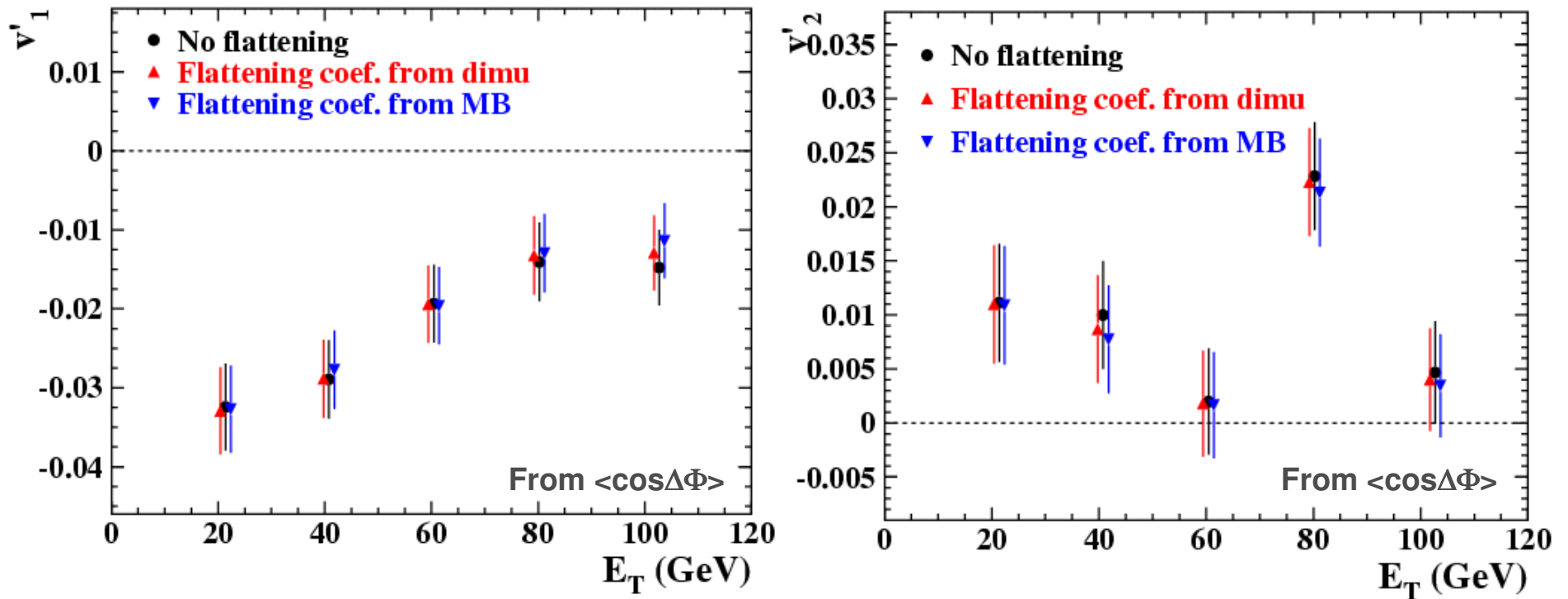
Cross-checks: E_{ZDC} centrality bins

- EMCALO used both for event plane and for centrality determination
 $\Rightarrow E_{ZDC} \rightarrow$ independent centrality estimator



- Similar centrality dependence as from E_T analysis
 \Rightarrow Exclude a bias from centrality selection

Cross-checks: event-plane flattening



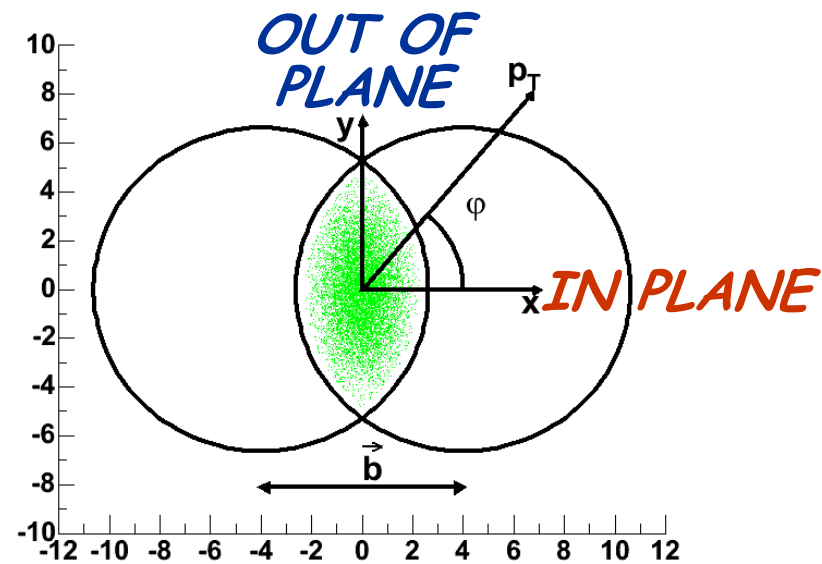
- Different choices of flattening the event plane do not change significantly v_n' results

Conclusions

- Preliminary results on J/Ψ production relative to the event plane in Pb-Pb collisions at 158 A GeV/c from NA50 experiment
 - ⇒ Event plane from azimuthal distribution of neutral transverse energy
 - ⇒ Correction for event plane resolution not applied
 - ✓ *presently under study*
- Negative J/Ψ v_1
 - ⇒ Unexpectedly large v_1 **BUT** momentum conservation effects not taken into account
 - ✓ *presently under study*
 - ⇒ More J/Ψ 's in the direction opposite to spectator nucleons, i.e. in the direction where more pions go
- Positive (in-plane) J/Ψ v_2
 - ⇒ More J/Ψ 's exiting "in plane"
 - ⇒ Indicates that breakup by comovers is not the main source of J/Ψ anomalous suppression

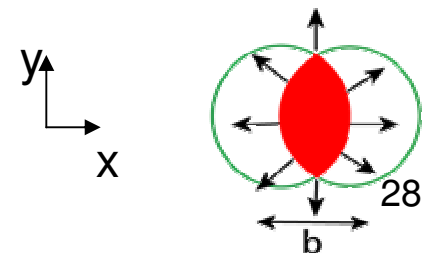
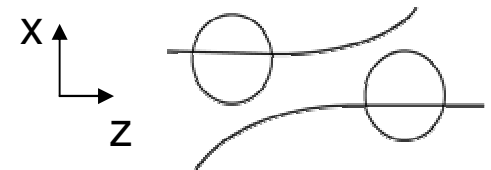
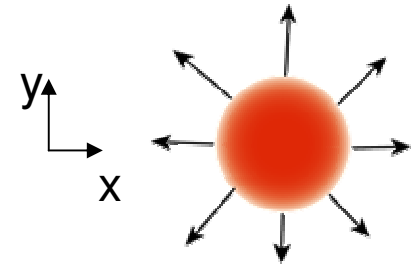
Backup

View in the transverse plane



Flow in the transverse plane

- **Flow** = collective motion of particles (due to high pressure arising from compression and heating of nuclear matter) **superimposed on top of the thermal motion**
 - ⇒ Flow is natural in hydrodynamic language, but flow as intended in heavy ion collisions does not necessarily imply (ideal) hydrodynamic behaviour
- **Isotropic expansion of the fireball:**
 - ⇒ Radial transverse flow
 - ✓ *Only type of flow for $b=0$*
 - ✓ *Relevant observables: p_T (m_T) spectra*
- **Anisotropic patterns:**
 - ⇒ Directed flow
 - ✓ *Generated very early when the nuclei penetrate each other*
 - Expected weaker with increasing collision energy
 - ✓ *Dominated by early non-equilibrium processes*
 - ⇒ Elliptic flow (and hexadecupole...)
 - ✓ *Caused by initial geometrical anisotropy for $b \neq 0$*
 - Larger pressure gradient along X than along Y
 - ✓ *Develops early in the collision (first 5 fm/c)*



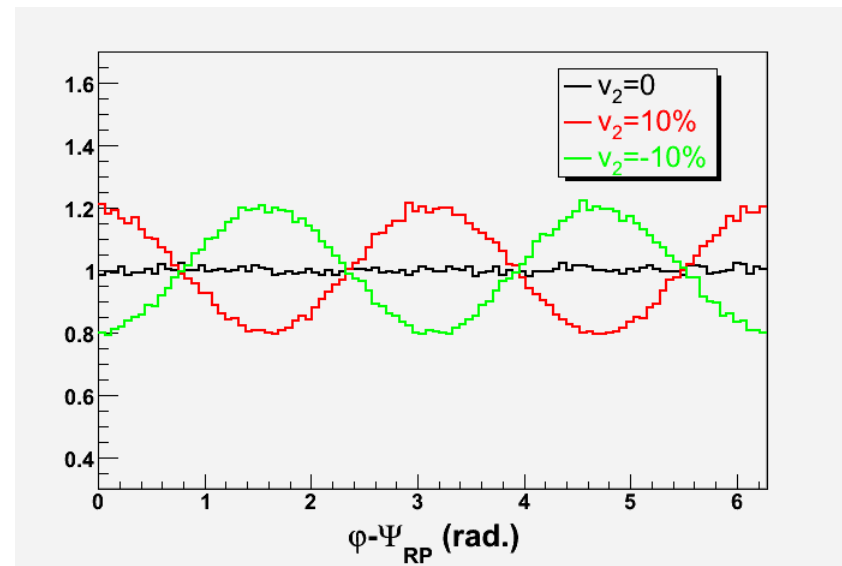
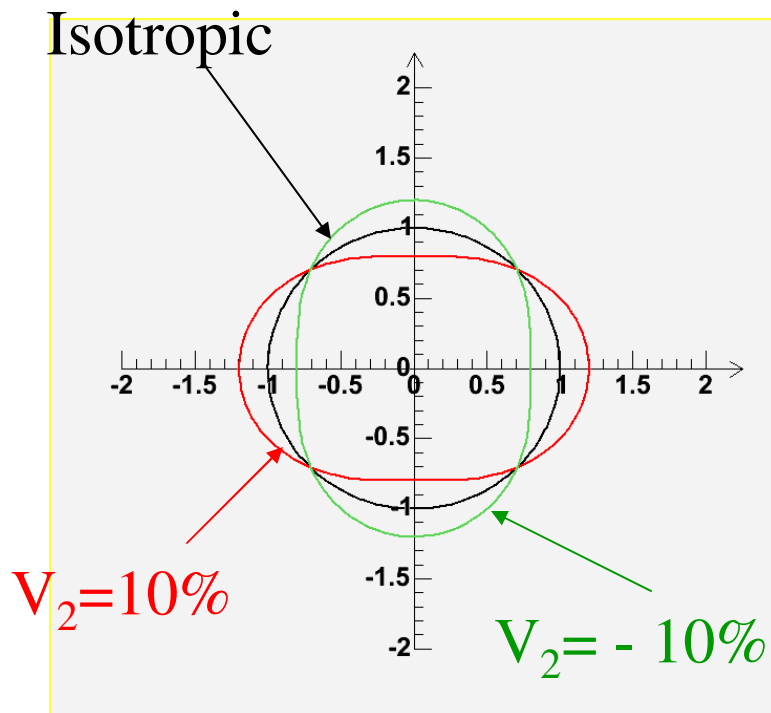
In-plane vs. out-of-plane

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi} \left(1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos(2(\varphi - \Psi_{RP})) + \dots \right)$$

Elliptic flow coefficient:

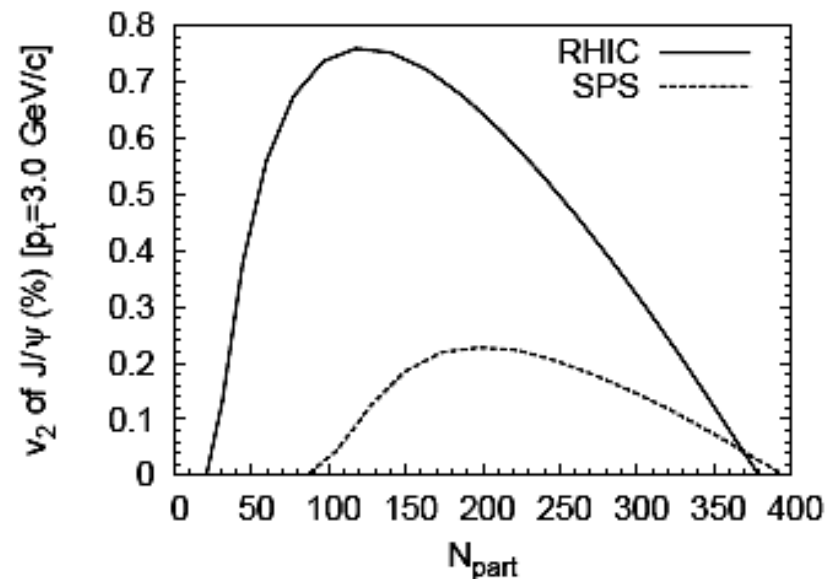
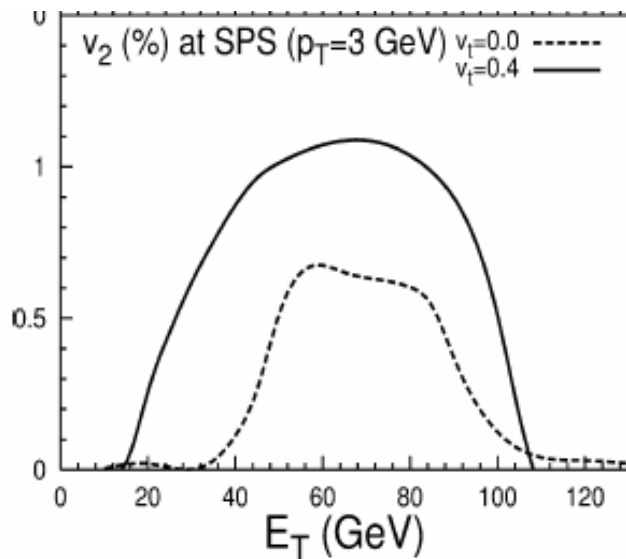
$v_2 > 0$ *In plane elliptic flow*

$v_2 < 0$ *Out of plane elliptic flow*



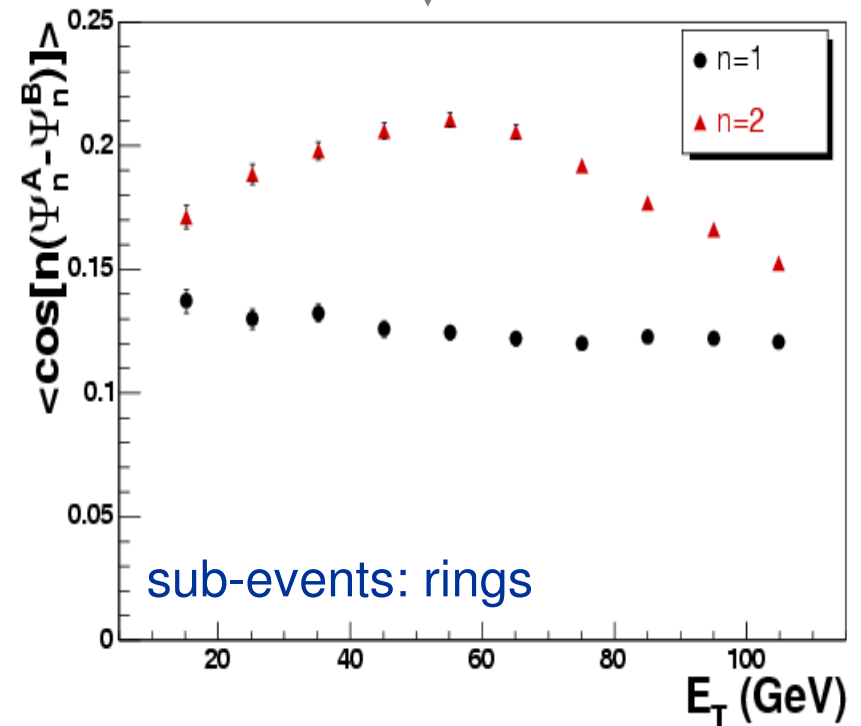
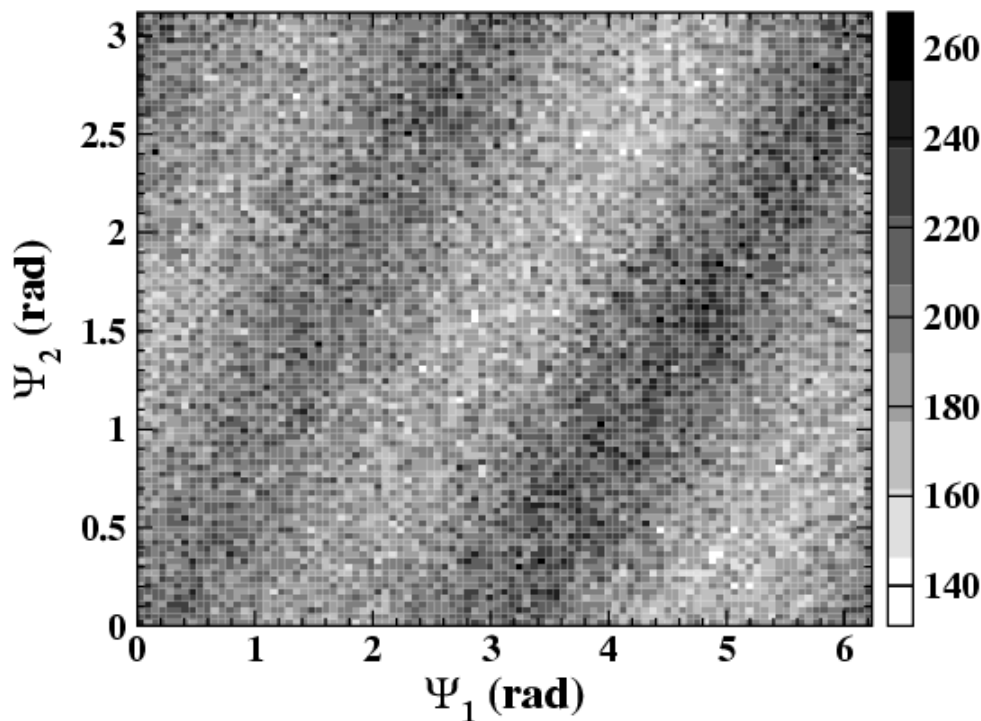
J/ψ anisotropy due to QGP

- Charmonium break p on hard gluons present in the deconfined medium
 - ⇒ Gluon density is not isotropic in non central collisions due to the almond shaped overlap region
 - ⇒ Sets in when the critical conditions for deconfinement are attained



Event plane resolution

- Can not define sub-events from azimuthal sectors (sextants)
 - ⇒ only 6 azimuthal sextants
- Can not define sub-events from radial (rapidity) sectors (rings)
 - ⇒ Non-flow correlations between contiguous rings
 - ⇒ Different number of particles hitting each ring
- Ψ_1 and Ψ_2 turn out to be well correlated

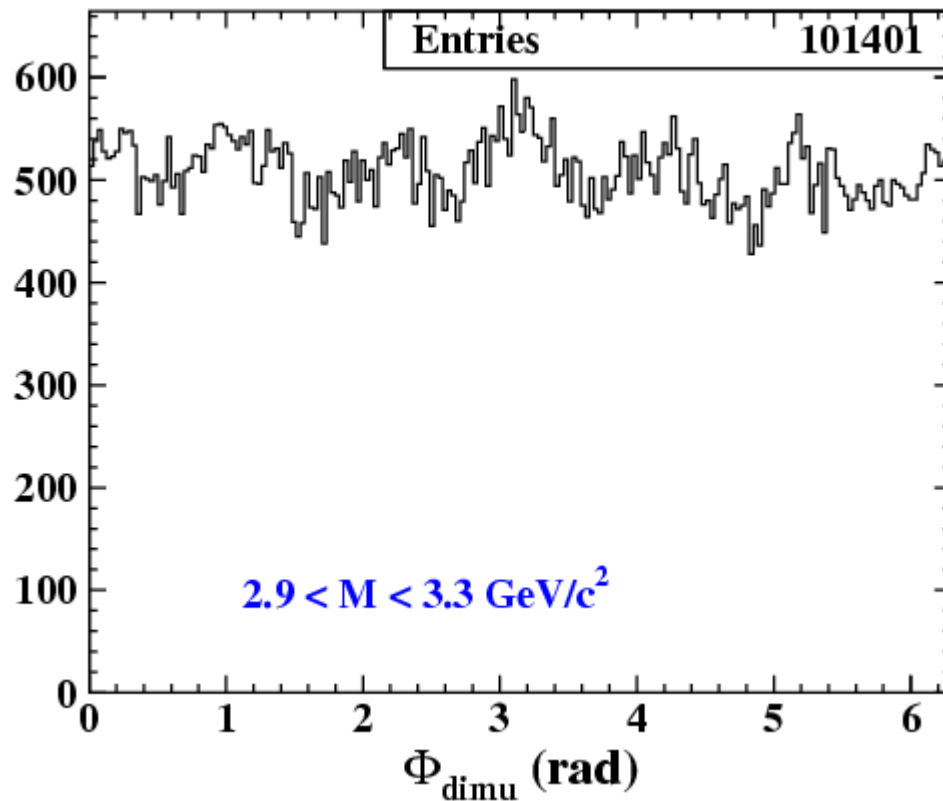


J/Ψ azimuthal distribution

- J/Ψ azimuthal angle from reconstructed muon momenta

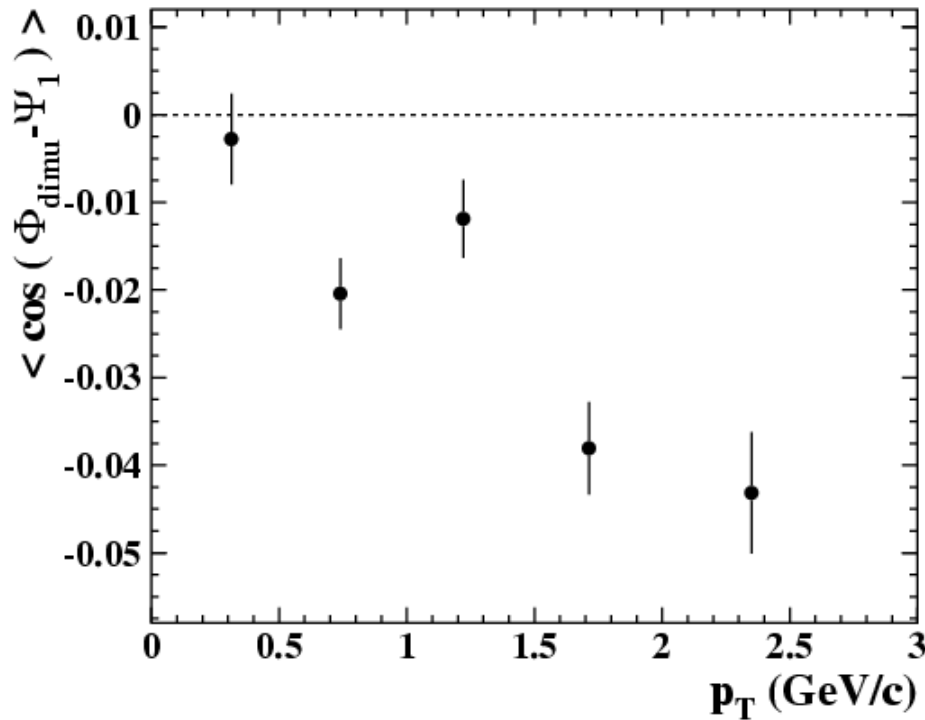
$$\Phi_{\text{dimu}} = \tan^{-1} \frac{p_y^{\mu 1} + p_y^{\mu 2}}{p_x^{\mu 1} + p_x^{\mu 2}}$$

⇒ azimuthal distribution not flat due to acceptance effects



p_T dependence of J/Ψ anisotropy

v'_1



v'_2

